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Search for CP-Violation in $\mathrm{K_S} \to 3\pi^0$ decays with the NA48 detector

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Abstract. The decay $\mathrm{K_S} \to 3\pi^0$ is forbidden by CP conservation. Using a sample of more than 6 million $K \to 3\pi^0$ decays, the NA48 Collaboration has improved the limit on $\eta_{000} = A(\mathrm{K_S} \to 3\pi^0)/A(\mathrm{K_L} \to 3\pi^0)$ and on the branching ratio $Br(\mathrm{K_S} \to 3\pi^0)$ by about one order of magnitude. Using this result and the Bell-Steinberger relation, a new limit on the equality of the K^0 and $\bar{\mathrm{K}}^0$ masses is obtained improving by about 40% the test of CPT conservation in the mixing of neutral kaons.

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1 Introduction

The NA48 experiment was optimized to measure the value of $Re(\epsilon\prime/\epsilon)$, i.e. the ratio of *direct* over *indirect* CP violation in the kaon sector [1], [2]. It took data between 1997 and 2001. The data taken during this period have been also used to perform a variety of other measurements of CP violation (η_{ooo} and K_{e3} charge asymmetry), mass and lifetime (K and η mass, K lifetime) and kaon and hyperon rare decays [3].

2 The NA48 Detector

The NA48 experiment is a fixed target experiment which uses two concurrent and quasi overlapping beams of kaons, Fig. 1. One kaon beam (called FAR beam) is produced 126 m upstream the other beam and by the time it reaches the decay region all its $\mathrm{K_S}$ mesons have decayed away. The second kaon beam (called NEAR beam) is produced only 6 m before the decay region and therefore contains both $\mathrm{K_S}$ and $\mathrm{K_L}$. The kaons are produced by a primary 450 GeV (400 GeV in 2001) proton beam ($\sim 1.5 \cdot 10^{12}$ per spill on the FAR target and $\sim 3. \cdot 10^7$ on the NEAR target) impinging on a 400 mm long, 2 mm diameter rod of beryllium. Charged particles from decays are measured by a magnetic spectrometer composed by four drift chambers with a dipole magnet between the second and third one which introduces a momentum kick of 265 MeV/c in the horizontal plane. The space point resolution is $\sim\ 95\mu m$ and the momentum resolution is $\sigma(p)/p = 0.48\% \oplus 0.009\% * p[GeV]$ (2001 values). The spectrometer is followed by a liquid kripton calorimeter 27 radiation length long with an energy resolution of $\sigma(E)/E = (3.2 \pm 0.2)\%/\sqrt{E} \oplus (9 \pm 1)\%/E \oplus (0.42 \pm 0.05)\%$. The detector is complemented by an hadronic calorimeter, a muon detector, fast hodoscopes for triggering, a proton tagging system, beam monitors. A full description can be found in [1],[2].

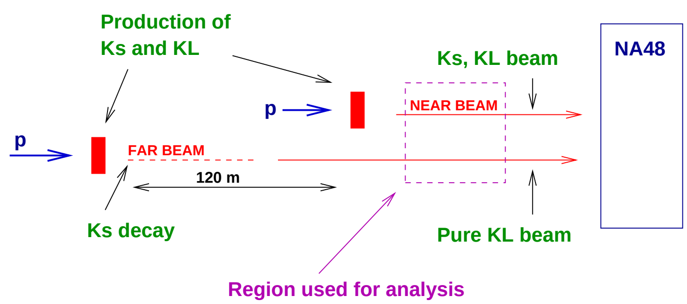

Fig. 1. The beam structure of the NA48 experiment

3 The Kaon system

The K^0 ,$\bar{\mathrm{K}}^0$ flavour eigenstates are created by strong interaction. These states mix and propagate as mass eigenstates, $\mathrm{K_S}$ and $\mathrm{K_L}$, which are a superposition of CP eigenstates: $\mathrm{K_S}$ is a quasi pure $CP = 1$ state and $\mathrm{K_L}$ a quasi pure $CP = -1$ state, Tab. 1. There is therefore a mismatch between the CP and the mass eigenstates which allows both $\mathrm{K_S}$ and $\mathrm{K_L}$ to decay into states of opposite CP.

Consider now the decay $K \to 3\pi^0$. Let's calculate the P, C and I values of a $|3\pi^0>$ state. The parity is given by $P|3\pi^o> = (-1)^l(-1)^L(-1)^3|3\pi^o>$ where l is the angular momentum of a pair of π^o, L is the angular momentum of the third π^o with respect of this pair and $(-1)^3$ is the intrinsic parity of a $|3\pi^0>$ state. Since the total angular momentum is $J = 0$ then $l = L$ and $P|3\pi^o> = (-1)^{2l}(-1)^3|3\pi^o> = -|3\pi^o>$. The charge conjugation operation on a π^o does not change its state,

Table 1. Kaon Eigenstates

Eigenstate	expression	CP value
Strong	$\bar{K}^0$ $(\bar{d}s)$, K^0 $(d\bar{s})$	
CP	$K_1 \propto (K^0 + \bar{K}^0)$	+1
CP	$K_2 \propto (K^0 - \bar{K}^0)$	-1
Mass	$K_S \propto K_1 + \epsilon K_2$	Almost +1
Mass	$K_L \propto \epsilon K_1 + K_2$	Almost -1

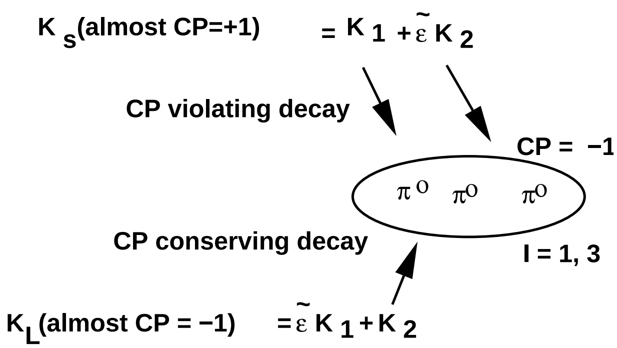

Fig. 2. $K_S \to 3\pi^0$ and $K_L \to 3\pi^0$ decay mode

$C|\pi^o>=|\pi^o>$ so we have $C|3\pi^o>=(+1)^3|3\pi^o>=+|3\pi^o>$. The isospin values of a $|3\pi^0>$ state are I=1 and I=3, which are both symmetric. The total wavefunction $|3\pi^0>=|spin>|space>|isospin>$ must be symmetric (three identical bosons) so both isospin values are allowed (the $|spin>|space>$ component, with $S=0$ and $l+L=0$ is of course symmetric). We have then: $CP|3\pi^o>=-|3\pi^o>$ with $K_L \to 3\pi^0$ a CP conserving decay and $K_S \to 3\pi^0$ a CP violating decay, both with $\Delta I = 1/2, 5/2$, Fig. 2.

4 η_{ooo}

In order to quantify the strength of CP violation in the $K_S \to 3\pi^0$ decay the following quantity has been introduced [4]:

$$\eta_{ooo} = \frac{A(K_S \to 3\pi^0)}{A(K_L \to 3\pi^0)}. \quad (1)$$

Assuming CPT invariance, using the Wu-Yang phase convention ($Im(a_0) = 0 \to \epsilon = \tilde{\epsilon}$) and ignoring transition into I=3 final states η_{ooo} can be rewritten as:

$$\eta_{ooo} = \epsilon + i\frac{Im(a_1)}{Re(a_1)} \quad (2)$$

where a_1 is the weak amplitude for K^0 to decay into I=1 final states and ϵ can be derived from the $K_L \to \pi\pi$ decay. In eq. 2 $Re(\eta_{ooo}) = Re(\epsilon)$ so it's only the immaginary part which is sensitive to direct CP violation.

5 The method

Given the very small (still unknown) branching fraction it's very hard to measure directly the decay $K_S \to 3\pi^0$. However, it's possible to see it's presence since it interferes with the much larger decay $K_L \to 3\pi^0$: given a $K_S + K_L$ beam, the intensity of $3\pi^o$ decay is given by

$$I_{3\pi^o}(t) \propto \underbrace{e^{-\Gamma_L t}}_{K_L \text{ decay}} + \underbrace{|\eta_{ooo}|^2 e^{-\Gamma_S t} +}_{K_S \text{ decay}}$$

$$\underbrace{+2D(p)[Re(\eta_{ooo})cos\Delta mt - Im(\eta_{ooo})sin\Delta mt]e^{0.5(\Gamma_S+\Gamma_L)t}}_{\text{interference } K_S - K_L}$$

where $D(p) = N(K^0 - \bar{K}^0)/N(K^0 + \bar{K}^0) \sim 0.35$, the dilution factor, parametrizes the K^0, $\bar{K}^0$ production asymmetry as a function of the kaon momentum. The maximum interference is at the target and most of the effect is contained within the first 2 K_S lifetime. The interference pattern is superposed over a large $K_L \to 3\pi^0$ signal and it can be positive or negative depending on the value of η_{ooo}, Fig. 3. The technique used for the measurement is therefore the following: 1) measure the intensity of $K \to 3\pi^0$ decay in the $K_S + K_L$ beam as a function of proper K_S time, 2) measure the same intensity for a pure K_L beam, 3) correct the two intensities for small differences between beams and systematic effects, 4) calculate the ratio of intensities and fit the interference term.

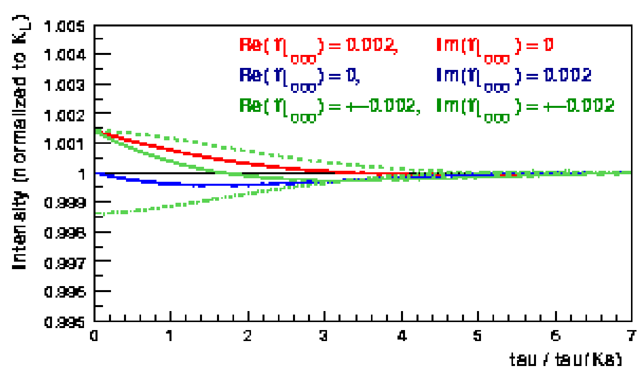

Fig. 3. Interference pattern for different values of η_{ooo} normalized to $K_L \to 3\pi^0$.

6 Data sample

This analysis have been performed using the data taken during the 2000 run. A sample of $6 \cdot 10^6$ $K_S + K_L \to 3\pi^0$ decays from the NEAR target and $\sim 10^7$ $K_L \to 3\pi^0$ decays from the FAR target have been collected, Fig. 4. To extract η_{ooo} a fit to the ratio of the NEAR/FAR samples is performed in kaon energy bins ($75 < E_K < 150$ GeV).

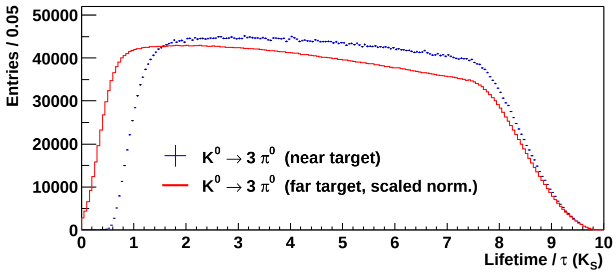

Fig. 4. $K \to 3\pi^0$ decays from the FAR and NEAR target in unit of K_S proper time

Table 2. Source of systematic errors

	Re $\eta_{ooo}(10^{-2})$	Im $\eta_{ooo}(10^{-2})$
Accidentals	± 0.1	± 0.6
Energy scale	± 0.1	± 0.1
Dilution	± 0.3	± 0.4
Acceptance	± 0.3	± 0.8
Binning	± 0.1	± 0.2
Total	± 0.5	± 1.1

Tab. 2 shows the sources of systematic errors. The systematics are dominated by uncertainties in the detector acceptance, accidental activity and the K^0 , $\bar{K}^0$ dilution.

7 Results and discussion

The result of the simultaneous fit to all energy bins is:

$$Re(\eta_{ooo}) = -0.026 \pm 0.01_{stat}$$

$$Im(\eta_{ooo}) = -0.034 \pm 0.01_{stat}$$

$$Br(K_S \to 3\pi^0) < 1.4 \cdot 10^{-6} \; 90\%CL.$$

The values of $Re(\eta_{ooo})$ and $Im(\eta_{ooo})$ have a correlation coefficient of 0.8. According to eq. 2 the constrain $Re(\epsilon) = Re(\eta_{ooo})$ can be used in the fit changing the results to:

$$Im(\eta_{ooo}) = -0.012 \pm 0.007_{stat} \pm 0.011_{sys}$$

$$Br(K_S \to 3\pi^0) < 3.0 \cdot 10^{-7} \; 90\%CL.$$

Fig. 5 shows these numbers while Tab. 3 lists the results of other experiments. NA48 has improved the precision of both η_{ooo} and $Br(K_S \to 3\pi^0)$ by an order of magnitude.

7.1 The Bell-Steinberger relation

Consider a kaon state, superposition of K_S and K_L, $|K(t)>= a_S K_S + a_L K_L$. Conservation of probability requires that the time derivative of this state is equal to the sum of the decay rates [5]:

$$-\frac{d}{dt}| < K(0)|K(0) > |^2 = \sum |a_s A(K_S \to f) + a_L A(K_L \to f)|^2.$$

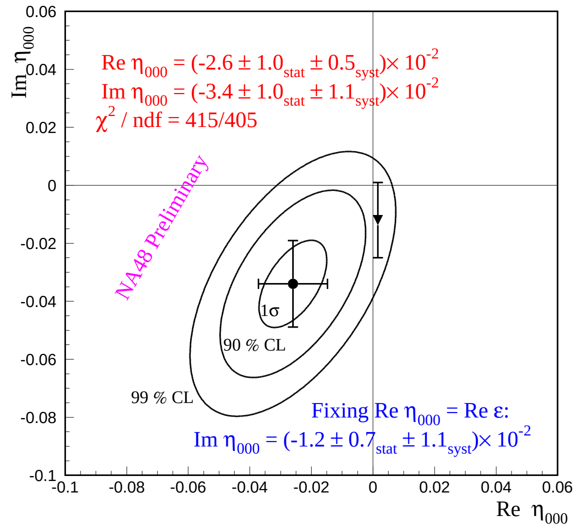

Fig. 5. Fit results for η_{ooo} assuming or not $Re(\epsilon) = Re(\eta_{ooo})$

Table 3. Results from other experiments

Exp.	Year	Technique	Result
FNAL-E621	1994	$K^0 - \bar{K}^0$ incoherent	Im $\eta_{+-o} = -1.5 \pm 1.7 \pm 2.5 \cdot 10^{-2}$
CERN	1998	$p - \bar{p} \to K^- \bar{K}^0 \pi^+$	Re $\eta_{+-o} = -2 \pm 7^{+4}_{-1} \cdot 10^{-3}$
CPLEAR		$\to K^+ \bar{K}^0 \pi^-$	Im $\eta_{+-o} = -2 \pm 9^{+2}_{-1} \cdot 10^{-3}$
Barmin	1983	Bubble ch.	Re $\eta_{ooo} = -8 \pm 18 \cdot 10^{-2}$
et al.			Im $\eta_{ooo} = -5 \pm 27 \cdot 10^{-2}$
CERN	1998	$p - \bar{p} \to K^- \bar{K}^0 \pi^+$	Re $\eta_{ooo} = 18 \pm 14 \pm 6 \cdot 10^{-2}$
CPLEAR		$\to K^+ \bar{K}^0 \pi^-$	Im $\eta_{ooo} = 15 \pm 20 \pm 3 \cdot 10^{-2}$
Novosibirsk SND	1999	Tagged K_s $ee \to \phi \to K_S K_S$	$Br(K_S \to 3\pi^0) < 1.4 \cdot 10^{-5}$

This relation can be rewritten as:

$$(1 + i\; tan(\phi_{SW}))[Re(\epsilon) - i\; Im(\Delta)] = \sum \alpha_f$$

with $tan(\phi_{SW}) = 2\Delta m/(\Gamma_S - \Gamma_L)$, $\alpha_f = 1/\Gamma_S A^*(K_S \to f)A(K_L \to f)$ the possible decays ($K_L \to \pi\pi$, $K_S \to 3\pi^0 ...$) and Δ the magnitude of CP violation with CPT violation. This identity therefore constrains CPT via the value of $Im(\Delta)$ which, with the new value of $\alpha_{ooo} = \frac{\tau_s}{\tau_L}\eta_{ooo}Br(K_L \to 3\pi^0)$, is reduced by almost 40%:

$$Im\Delta = (2.4 \pm 5.0) \cdot 10^{-5} \to Im\Delta = (-1.2 \pm 3.0) \cdot 10^{-5}.$$

$Im(\Delta)$ is now limited by the knowledge of η_{+-}. Assuming CPT this result can be converted into a new limit on the K^0 , $\bar{K}^0$ mass difference:

$$m_{K^0} - m_{\bar{K}^0} = (-1.7 \pm 4.2) \cdot 10^{-19} GeV/c^2.$$

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